The Constellation-X SXT Optical Alignment Pathfinder 2 – Design, Implementation and Alignment

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ABSTRACT

The Constellation-X SXT mirrors and housings continue to evolve toward a flight-like design. Our second-generation alignment housing, the Optical Alignment Pathfinder 2 (OAP2), is a monolithic titanium structure that is nested inside the OAP1 alignment jig, described in a previous paper (J. Hair, et. al., SPIE 2002[1]). In order to perform x-ray tests in a configuration where the optical axis is horizontal, and continue to develop more flight-like structures, we needed to design a strong, but lightweight housing that would impart minimal deformations on the thin segmented mirrors when it is rotated from the vertical orientation used for optical alignment to the horizontal orientation that is used for x-ray testing.

This paper will focus on the design of the OAP2 housing, and the assembly and alignment of the optics within the OAP1 plus OAP2 combination using the Centroid Detector Assembly (CDA). The CDA is an optical alignment tool that was successfully used for the HRMA alignment on the Chandra X-ray Observatory. In addition, since the glass we are using is so thin and flexible, we will present the response of the optical alignment quality of a Wolter-I segment to known deformations introduced in by the OAP1 alignment housing.

Keywords: Segmented Optics, Optic Alignment, Optical Metrology, Centroid Detector Assembly

1. INTRODUCTION

The Optical Alignment Pathfinder 2 (OAP2) is the second generation housing in a series that will allow us to predict, measure, and understand the performance of thin, replicated glass, segmented x-ray mirrors. Made from a single, annealed block of titanium, the OAP2 is a stiff, monolithic unit designed to impart minimal distortion on test mirrors when they are aligned vertically, and tested horizontally. It fits inside the existing Optical Alignment Pathfinder 1 (OAP1) structure for alignment and bonding, and allows for simultaneous axial interferometry and average slope angle correction using the Centroid Detector Assembly (CDA).

Using this combination, we evaluated the mechanical flexibility of our replicated glass mirrors, and have determined a range of corrections that can be applied to out-of-specification mirrors, including correcting the average slope angle and the axial sag (2nd order figure error) in order to obtain a focused image, and optimal axial figure. We present our tools for this study, the alignment process used for the mirrors, and the mechanical performance of test mirrors in deliberately deformed states.

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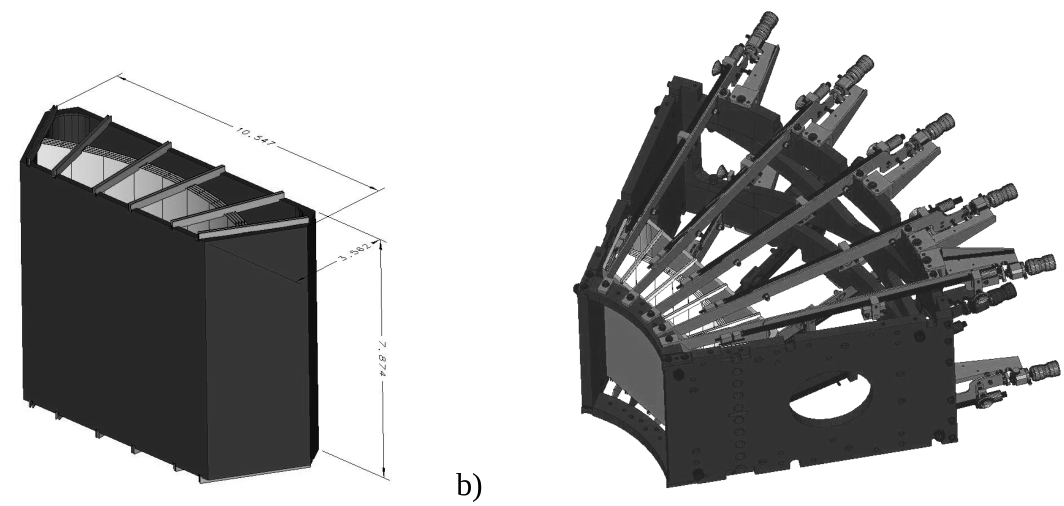
2. OPTICAL ALIGNMENT PATHFINDER 2

Design

A schematic of the OAP2 is shown in Figure 1a. The OAP2 housing is a monolithic titanium structure EDM machined out of a single block of pre-annealed titanium. This method of manufacturing minimizes the amount of internal stress that would otherwise be introduced with normal machining practices. It was designed to nest inside the OAP1 housing so that we could continue to use the OAP1 precision alignment arms, as shown in Figure 1b. During alignment of a mirror, the OAP1 and OAP2 units sit kinematically on separate sets of tooling balls, so that there is no direct contact between them.



a) b)

Figure 1. a) Schematic of the OAP2 module. b) Combination of the OAP2 inserted in the OAP1 alignment housing.

The OAP2 unit uses a series of six radial support arms to hold the mirror in place. These are U-channels cut from that same stock titanium as the housings. Each arm has five grooves cut where the mirror slides through. The mirror can then be bonded in place where it protrudes through the arm.

Mechanical Properties

The OAP2 housing was deliberately designed thicker than any flight-like hardware because of the need to decouple 1-G optic deformations from 1-G housing deformations. Furthermore, alignment of the mirrors with the CDA and *in-situ* interferometer takes place with the optical axis vertical, while x-ray testing will be done horizontally. As such, the housing needs to be very stiff so that it will not sag under different orientations. Finite element modeling indicates that the error introduced in the x-ray image due to the 1-G gravity sag of the OAP2 housing is 7.1 arcseconds. This effect is thoroughly examined in a separate paper in these proceedings[2].

Thermal Properties

A common titanium alloy was chosen, as it is a readily available material, and has a CTE close to that of the glass used for the segmented mirror substrates (DESAG 263). The CTE of the titanium is 8.6×10^{-6} per degree C, while the glass CTE is 6.3×10^{-6} per degree C. (While these are not CTE matched *per se*, we are investigating a variety of titanium alloys that have a much closer match to the glass substrates we are using.) If the system is tested at a different temperature than it was bonded at, the CTE mismatch will introduce strains in the glass. As such, the temperature of the entire unit needs to be held to within 1 degree

C of the bonding temperature, and the temperature non-uniformity across the housing should be no more than 0.1 degree C. Again, these effects are fully examined in Reference 2.

3. CENTROID DETECTOR ASSEMBLY

Basics

The Centroid Detector Assembly (CDA) is a modified Hartmann system to gauge the wavefront error induced by a non-ideal grazing incidence optic. This instrument was first used to align the HRMA aboard the Chandra X-ray Observatory, and its specifics and function are described elsewhere[3]. Its application to the Constellation-X SXT was revisited in a previous paper[1]. In brief, the CDA employs a pointed laser beam system that maintains a constant point source position, no matter where the beam is pointed. There is also a beam splitter module that redirects the return beam to a carefully calibrated quad-cell photodiode that determines the position of the centroid of the return beam to within less than 1 arcsecond precision. The beam can be scanned along the azimuth of a grazing incidence mirror or mirror pair, and the average cone angle along the footprint of the beam can be determined accurately.

In order to test either individual mirrors or mirror pairs, the CDA was mounted in our laboratory with a series of fold mirrors (see Figure 2). Their position allowed us to conveniently change the path length of the system from the 16.8 meter focal length of a single primary mirror to the 8.4 meter focal length of a Wolter-I pair. Alignment of a secondary (hyperboloid) mirror alone requires moving the CDA forward toward the tower (5.6 meter focal length), and is not shown in this schematic.

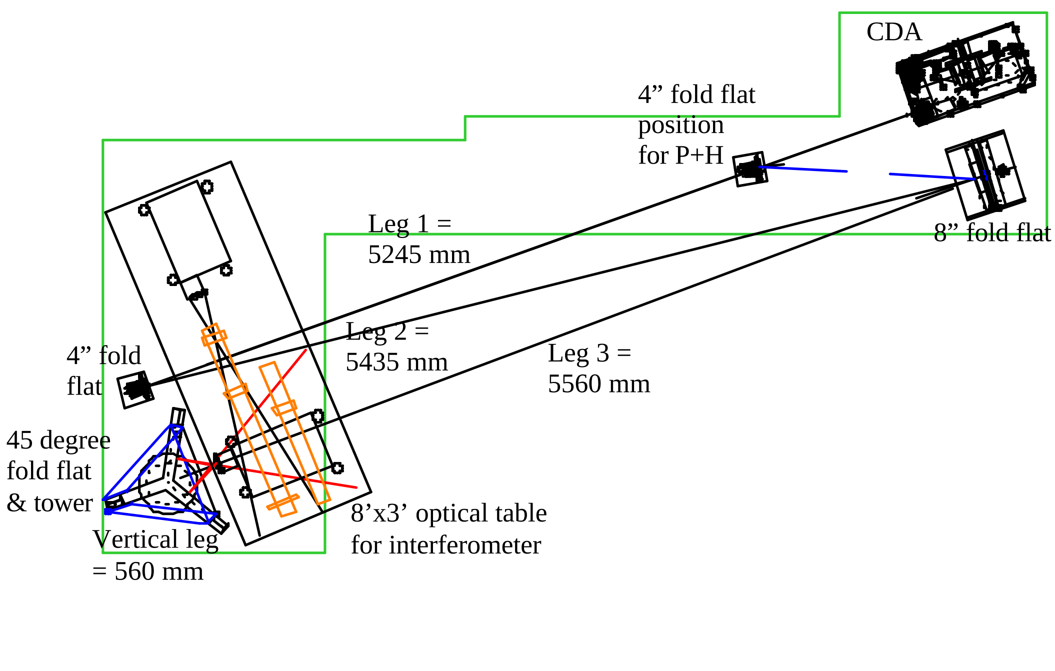


Figure 2. Layout of the CDA beam path. The outline around the experiment is the available space on the optical table. The 8’ x 3’ optical table is mounted above the CDA beam path, at a similar height to the OAP2 housings.

Not shown in this schematic is that the CDA is mounted on a set of precision rails, allowing the user to move the CDA away from the ideal focal length and test imaging away from the focal point of a mirror or mirror pair.

4. *IN-SITU* INTERFEROMETER

In addition to the CDA, a normal incidence interferometer (Wyko 400) is used to gauge the alignment quality of the test mirror. Since the CDA only yields average cone angle, we need to also know the axial figure of a mirror, at a variety of azimuthal positions. A schematic of the axial interferometer is shown in Figure 2, and the hardware itself is shown in Figure 3. The focused beam coming out of the interferometer is collimated by an 8” off-axis parabola. That collimated beam is redirected to the mirror surface, where a narrow axial stripe of light is retro-reflected back to the interferometer. By redirecting the collimated beam to different azimuthal positions along the mirror, the axial figure at a series of locations can be determined. That, in combination with the average cone angle measurement of the CDA yields the information necessary to align a mirror.

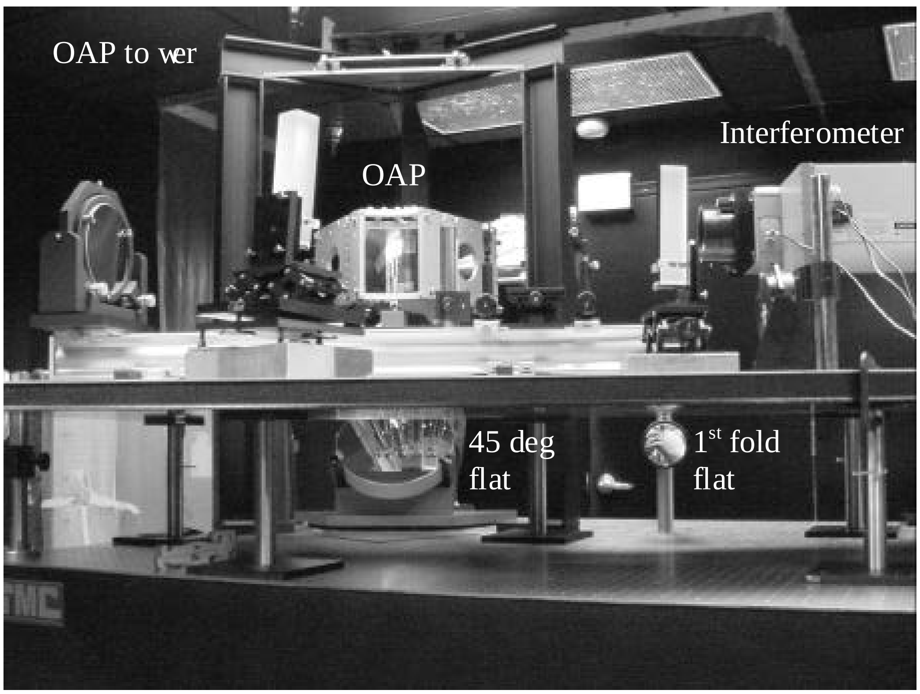


Figure 3. The *in-situ* interferometer sits on a raised optical table, allowing the CDA beam to traverse unobstructed across the main optical table.

The interferometer can also be placed in a secondary position so that the circularity of the mirror in question can be tested. This involves placing the focusing lens of the interferometer very close to the optical axis of the test mirror such that a narrow horizontal stripe is reflected back into the interferometer. This is a difficult test, as alignment of the interferometer’s focal point must be precisely on the optical axis of the telescope mirror, and testing multiple points along the axial length requires moving the interferometer up and down, making it necessary to realign the interferometer at each point.

However, this has been done on a few mirrors, primarily to test the accuracy of the initial CMM alignment. These tests are done before any alignment is done using the CDA or axial interferometer, since neither of these instruments can gauge the circularity. A set of example circularity profiles is shown in Figure 4.

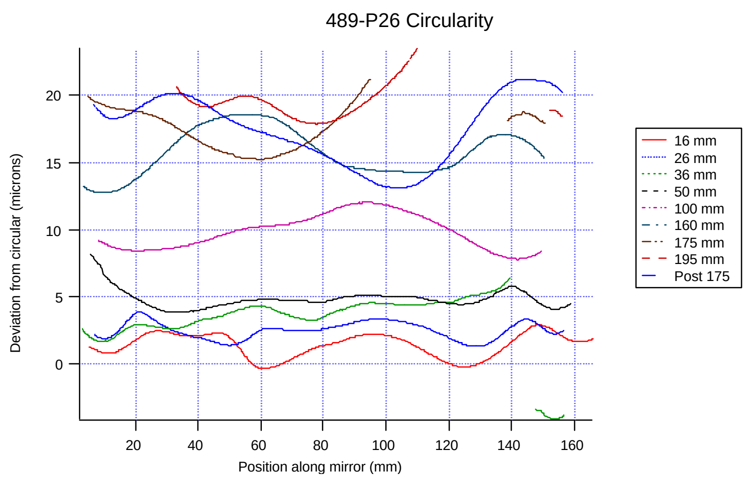


Figure 4. Interferometric circularity from test mirror in an OAP1 housing. Individual traces are offset by an amount proportional to their axial position along the mirror.

5. ALIGNMENT AND PERFORMANCE

Alignment

Alignment of a mirror pair requires a large number of setup steps, as well as the number of steps in the actual manipulation of the mirror. The entire process, as developed so far, is outlined here.

Setup mirror in OAP1/OAP2 combined unit.

1. Position the bottom support struts on the OAP2 using a coordinate measuring machine (CMM) with ~2.5 μm absolute accuracy. Bond these in place[4].
2. Insert the mirror to be tested and position and bond the top support struts with the CMM.
3. Insert the OAP2 unit inside the OAP1 housing, each resting on separate kinematic mounts.
4. Capture the mirror with the 10 ruby ball tipped alignment arms, and adjust the front surface of the mirror at these 10 points to the designed radius using the alignment actuators and the CMM as feedback.

Setup CDA beam path

1. Define “zero level”. (The entire optical path is setup on a vibration isolated optical table, whose level can shift if the components on the table shift position. As such, using a gravity-based level is inconvenient since it does not have a constant reference with respect to the table surface.) The “zero level” is defined by third leg of the beam path.
    a. Set the CDA beam to its central position
    b. Position fold flats so that the CDA is at the nominal focal length
    c. Adjust the first two fold flats such that the beam height through the third leg of the optical path is optimal and is parallel to the surface of the optical table (i.e., the center of the beam at each end of the third leg is the same distance from the table surface).
2. Adjust the 45-degree fold flat such that the beam reflected off of the retro-flat at the top of the alignment tower returns to the center of the CDA detector. There is no absolute reference for the tip and tilt of the retro-flat, and so the 45-degree flat will not necessarily be at 45 degrees.

(Measurements of the axial sag of test mirrors show little change with tilt angle away from the gravity vector. So, the absolute angle of the vertical leg of the optical path is not currently of significant consideration.)

3. Tilt the 45-degree flat back by half of the cone angle of the test mirror.
4. Mount the OAP1/OAP2 test mirror unit. Adjust the lateral position of the 45-degree fold flat so that the CDA beam strikes the center of the test mirror.
5. Without the aperture mask plate above between the mirror and the retro-reflector, roughly align the rigid-body tilt and roll of the mirror housing. (This is done without the mask plate to make the CDA return beam easier to see by eye.)
6. Install the mask plate and align it over the mirror.

Align mirror

1. Determine the position of the return beam at each azimuthal end and the center of the mirror. The nature of the OAP1 mechanism only allows one to adjust the radial positions of mirror. As such, the beam coming from the center of the mirror will only move up and down, while the beam from each azimuthal end will move in a line ±30 degrees from the vertical. Tracing these lines from the three points yields an intersection point where all return beams should eventually be focused.
2. If the three lines will not intersect, the cone angle of the system may not be correct. Adjust the angle of the 45-degree flat and compensate by changing the rigid-body angle of the OAP housing. This effectively changes the focal length of the system, and will bring the two azimuthal spots closer or further away from the central spot.
3. Take an initial series of axial interferograms.
4. Once the optimum tilt angles are set, proceed by adjusting each of the five sets of OAP1 actuators in order, while monitoring a CDA spot close to that alignment arm. Pairs of top and bottom actuators should be moved differentially (one in and one out by the same amount) in order to minimize the impact on axial figure. Move each of the actuator pairs until the respective CDA spot moves to the focal point determined above.
5. Once optimal alignment of all CDA spots is achieved, take another set of axial figure scans to gauge the impact of the alignment procedure and determine whether the axial figure at any of the azimuthal positions should be adjusted. If so, moving pairs of actuators in common mode (either both in or both out) can change the second order axial figure, as shown in Figure 8. An example final CDA alignment is shown in Figure 5.

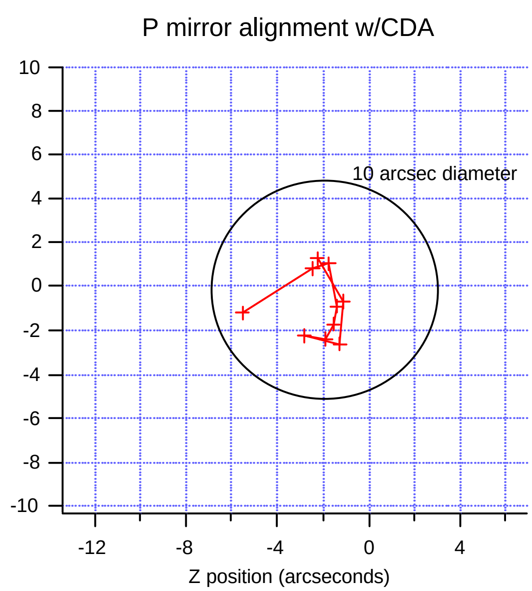


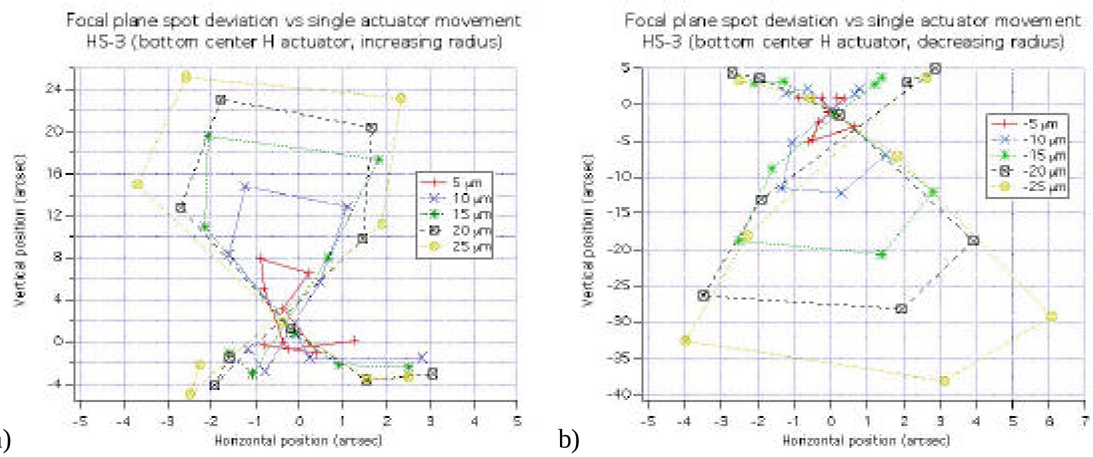
Figure 5. Single mirror CDA image.

Bonding
Once the mirror has been aligned and the axial figure is optimized, the mirror is bonded into the OAP2 alignment grooves. Temperature stability is important at this point and after, in order to maintain figure and alignment quality.

Stacking
Once the mirror is bonded in place, the alignment fingers are released and the OAP1 structure is disassembled from around the OAP2. In the case of a primary mirror (now called the OAP2-P module), the module is mounted on top of another OAP1/OAP2 combination with a secondary mirror installed (the OAP2-H). The OAP2-P module is placed on top of that, while the secondary mirror is aligned. This gives the user the opportunity to null out any misalignment of the primary mirror, due to bonding stress or poor local figure quality, etc.

Bonding P and H modules
Finally, once the OAP2-H module is aligned, bonded and removed, the OAP2-P and OAP2-H modules are placed on the CDA tower, where their relative alignment is checked again. They are then bonded together with a set of four t-bars, running axially along the front and back surfaces of the OAP2 housings.

Mirror deformation
Whenever one of the OAP1 alignment arms is adjusted, the mirror deforms in response. The propagation length of that deformation depends on the stiffness of the glass, and the distance to neighboring alignment arms. This dependence was tested by moving the bottom, center, OAP1 actuator a known amount and watching the deformation of the CDA image quality. The results are shown in Figure 6. The image deforms in an expected manner, consistent with FEM modeling.



a) b)

Figure 6. Image deformation in response to known movements of the bottom central actuator.

From these data, we extrapolated the necessary mirror deformation that would give rise to the image deformation seen above. It is seen that the deformation due to a small actuator movement propagates fully to the next alignment arm position, where it appears to be damped out by the ruby ball fingers that hold the mirror in place.

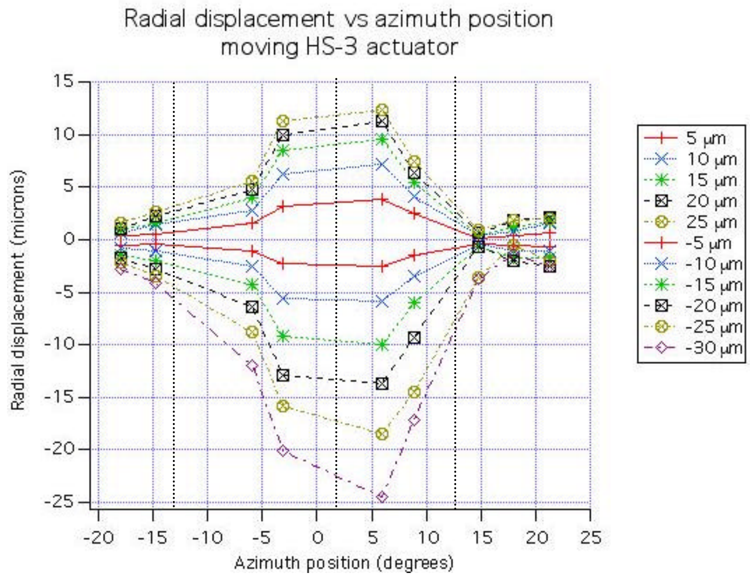


Figure 7. Mirror deformation extrapolated from the changes in the focal plane image from known movements of the bottom central actuator. The central three alignment arm positions are indicated by the vertical dashed lines at ±13 degrees and 2 degrees.

Axial figure sensitivity

Just as important as the average slope angle, as determined by the CDA, the correct axial figure of mirrors must be maintained during alignment to produce the Wolter-I focusing necessary to achieve the 5 arcsecond imaging goal. If the axial figure has a second order (sag) error, it can be compensated for, to some degree, by moving top and bottom pairs of actuators in common. The effect of this movement is shown in Figure 8, in coarse movements in part a, and fine movements in part b. The design for a 50 cm diameter shell specifies a smooth 1.1 µm peak-to-valley curvature, with a tolerance of 0.2 µm. We have found that a 1 µm common mode adjustment yields approximately a 0.2 µm P-V change in axial sag.

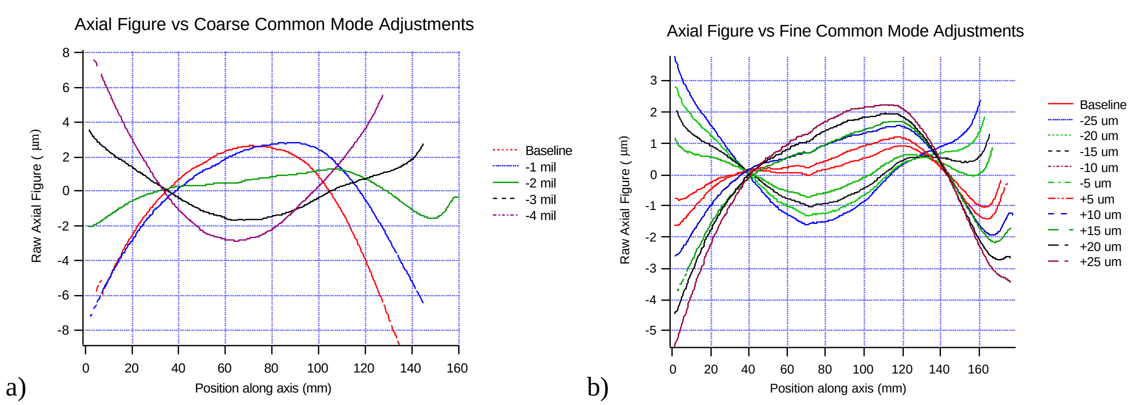


Figure 8. Axial figure at the center azimuth for different common mode adjustments.

Global radius change sensitivity

If the radius of curvature of the entire mirror is changed, by all 10 actuators in or out by the same amount, the axial figure will also change, but not as severely. As shown in Figure 9, the 2nd order axial figure changes by approximately 0.05 µm for every 1 micron of global radius change. This may become a problem if we find that our forming process produces mirrors with incorrect radius of curvature. For example, if the resulting radius of curvature is off by 10 µm, and we correct that during alignment, the axial sag at the center of the mirror will change by 0.2 µm, which is too large, assuming that the initial axial sag is correct. Also, the global radius of curvature change appears to introduce other higher order figure aberrations beyond 2nd order.

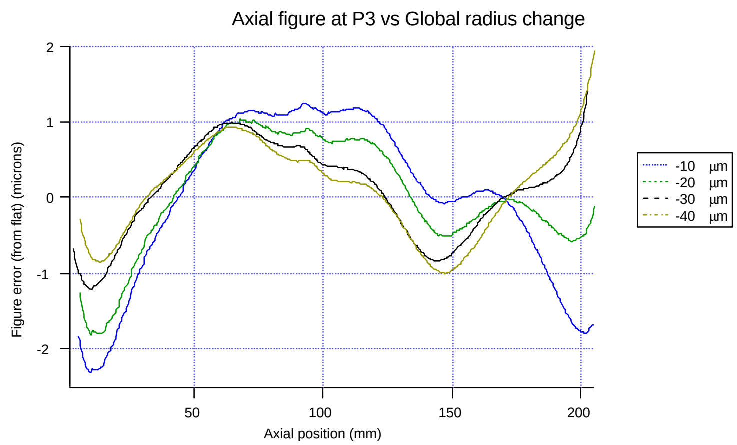


Figure 9. Axial figure change vs global radius of curvature.

6. CONCLUSIONS AND FUTURE WORK

The Optical Alignment Pathfinder 2 (OAP2) is the second generation housing in a series that will allow us to predict, measure, and understand the performance of thin, replicated glass, segmented x-ray mirrors. The OAP2 is a stiff, monolithic unit designed to impart minimal distortion on test mirrors when they are aligned vertically, and tested horizontally. It leverages the existing OAP1 structure for alignment and bonding, and allows for simultaneous axial interferometry and average slope angle correction using the Centroid Detector Assembly (CDA).

We have further evaluated the mechanical flexibility of our replicated glass mirrors, and have determined a range of corrections that can be applied to out-of-specification mirrors, including correcting the average slope angle and the axial sag (2nd order figure error). We plan to use two OAP2 modules, bonded together to form a Wolter-I pair, in an x-ray test at the Stray Light Facility at Marshall Space Flight Center in early 2004 to prove evaluate the imaging performance of these mirrors in operation.

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[1] J. H. Hair, *et. al*, "Constellation-X Spectroscopy X-Ray Telescope Segmented Optic Assembly and Alignment Implementation", *Proc. SPIE*, , (2002).
[2] W. A. Podgorski, *et. al*, "Constellation-X spectroscopy x-ray telescope image error budget and performance prediction", *Proc. SPIE*, 5168-35, eds. O. Citterio and S. L. O'Dell (2003).
[3] P. Glenn, *Centroid Detector Assembly for the AXAF-I Alignment Test System*, *Proc. SPIE* 2515, 352 (1995)
[4] All epoxy bonds in the OAP2 use Stycast 2850 epoxy.